Development of an Adaptive Vertical Coordinate Capability for Community Ocean Models

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LONG-TERM GOALS

The goal of this project is to develop state-of-the-art modeling technologies for accurate representation of the ocean system as it evolves in time and space. The proposed adaptive vertical coordinate system is one of the innovative technologies and will be applied to the ONR-initiated Expert System for use in a variety of ocean-related areas, including coupled physical-biogeochemical studies, climate simulations using combined atmosphere and sea-ice models, and coastal ocean predictions.

OBJECTIVES

The main objective of the proposed study is to develop an adaptive vertical coordinate capability for numerical ocean models. The coordinate system will be based on the best attributes of current known vertical coordinates, hence, should have the ability to enhance vertical resolution in the surface mixed layer for proper representation of thermo-dynamical and biogeochemical processes, to resolve the bottom boundary layer for coastal ocean processes, and to retain water mass characteristics for long-term simulations. The second objective of the study is to implement the proposed vertical system to community users ocean models. This useful tool will allow diverse ocean modelers to choose the optimal vertical model structure for a hierarchy of scales from coastal to global, and to easily coordinate and share modeling resources.

APPROACH

Our technical approach is based on several, recently developed modeling techniques: a smooth transition scheme, the general pressure gradient formulation, and the finite volume method.

The idea of smoothly transitioning among different coordinate structures is based on the successful implementation of the **s**-coordinate formulation in the S-coordinate Rutgers University Model (SCRUM, Song and Haidvogel 1994) and its expanded version, the Regional Ocean Modeling System (ROMS, Shchepetkin and McWilliams 2001). The **s**-coordinate system is a generalized sigma-coordinate to permit uniformly high resolution near the surface (like the z-coordinate) and preserve the bottom-following characteristic of the sigma-coordinate. The result is a smooth transition region in the vertical column, centered at the thermohaline depth h_c. The **s**-coordinate has the simple, infinitely

continuous, functional form: z = zeta(1+s) + h_c s + (h-h_c)C(s), where zeta(x,y,t) and h(x,y) are surface elevation and bathymetry, respectively, and C(s) is a set of s--curves, depending on two controlling parameters for surface layer and for bottom layer. By choosing the parameter appropriately, the highest resolution is achieved near the surface layer and/or bottom layer, independent of varying bottom topography.

Another key technique for developing the adaptive vertical scheme is Jacobian formulation method of calculating the pressure gradient force in a general vertical coordinate system (Song 1998). This scheme has proven to be more accurate than the traditional approach (Haney 1991) and greatly reduces hydrostatic inconsistence. Applications of this scheme are successful in ROMS for simulations of the California Current System (Song et al. 2001) and in a z-level model for BBL dynamics (Song and Chao 2000).

The finite volume method, which has been used for both incompressible and compressible flow, has two major advantages. First, it has good conservation (of mass, etc.) properties. Conservation of physical properties in ocean models is critical for long-term simulations, such as climate studies and for equilibrium circulation of coastal currents. Second, the finite volume method allows complicated computational domains to be discretized in a simpler way than either the isoparametric finite element formulation or generalized curvilinear coordinates. This method does not depend on the mesh regularity, but is suited to approximate mixed derivatives and degenerates into the finite difference method when the mesh is regular. This is another important issue in ocean modeling as the complex geometry, including islands, coastline, and headlands.

WORK COMPLETED

We have completed our first task in solving the technical problems by systematically testing the performance and evaluating the efficiency of the adaptive coordinate system. We have performed intercomparisons of different vertical structures. Mesh doubling calculations (Roache 1990) for ascertaining grid convergence has been used as the general practice for evaluating the numerical accuracy in engineering code development. We used this technique to test our numerical schemes. For example, there is no exact solution for the canyon test problem of Haidvogel and Beckmann (1999). To have benchmark solutions for the comparisons, we run the problem with a mesh doubling and with a mesh halving resolution. Then the solutions are compared to see where they converge to the mesh doubling solution. Although this method seems costly, it is so far the most reliable method to debug the code and to generate a reliable model for the community.

We have also completed our second task in demonstrating the model’s capabilities for multi-scale applications—coastal canyon, seamount topography, wind-driven double-gyre, and global ocean circulations. Our results show that the model is capable of resolving multi-scale processes with both compressible and incompressible flow conditions in the same numerical configuration. The inclusion of the compressible physics with out method does not incur computational expense, but more faithfully represents satellite sensing data, such as TOPEX sea-surface elevation and GRACE bottom-pressure anomaly, which directly measure the changes of the water mass, instead of the changes of the water volume. A manuscript is completed (Song 2002) and some of the results are reported bellow.

RESULTS

To test our proposed method of improving the simulation of the down slope transport of dense water, we applied the EBBL formulation of Song and Chao (2000) to a z-coordinate ocean model. The coupling between the interior z-level model and the EBBL model is achieved by exchanging entrainment/detrainment and pressure gradients at the bottom layer surface, which allows temporal and spatial variations. The nice feature of this simple test problem is that it allows the model to adjust itself by transporting cool water at lower layers to the deep ocean in exchange for warmer water from upper layers, rather than by a specified inflow, which forces the system. The dynamical processes associated with coastal density fronts and dense water plumes have been investigated (e.g., Whelless and Klinck 1995). Our model solutions (Figure 1) show dense coastal water at the bottom flowing down slope, being self-advected to the right and forming a plume, which are consistent with those early results.

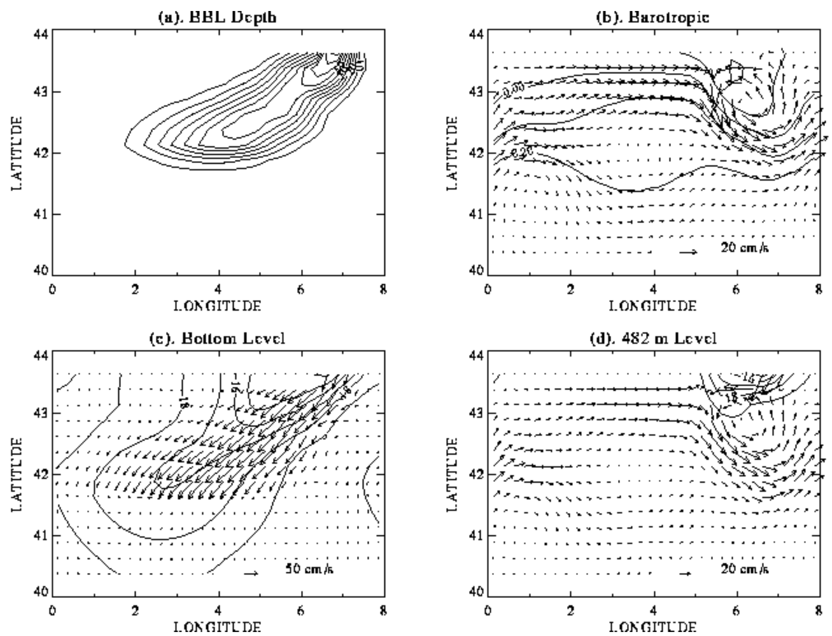

Figure 1: Model results for a plume test using EBBL scheme.

We have also succeeded in modeling the wrind-driven double-gyre circulations in compressible (non-Boussinesq) flow conditions. The problem tests the response of the model to wind forcing in a simple geometry and in the absense of any explicit diffusion of density. The wind drives a double-gyre with a western boundary current. The boundary current separate from the wall, extends far away across the domain and should produce eddies and shed rings. Although it has been modeled by a variety of ocean models, to our knowledge, such a problem with eddy-resolving resolution and compressible flow conditions has not been examuned beffore. Here, we impose a problem more challenging than thosed previously studied by adding a steep continental slope to the western side of the basin. The sloping topography should lead to an early separation of the western boundary current due to the JEBAR effect. One of the results is given in Figure 2, showing the circulation patern of cold and warm eddies detached from the western boundary current. The separation latitude of the boundary curent shifted south of the zero wind stress curl and a wedge of northern water advected further southward along the slope as expected.

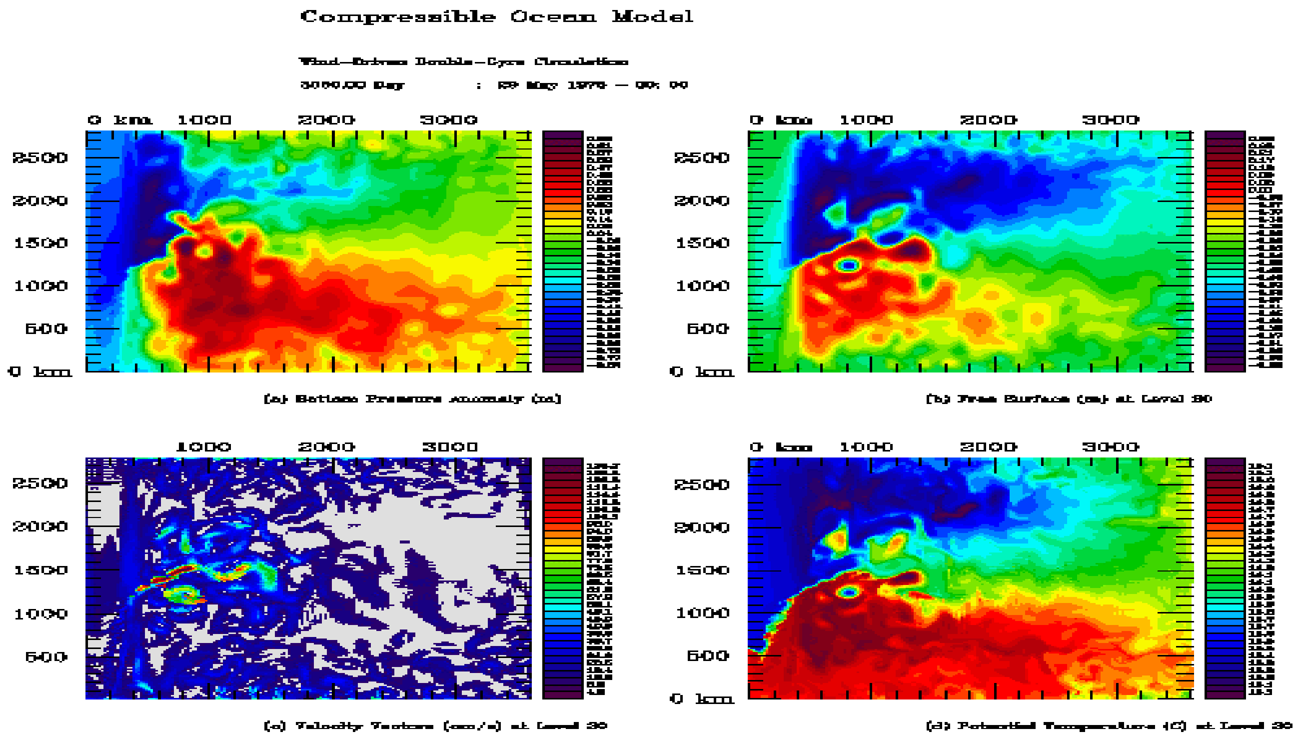

Figure 2: Non-Boussinesq model results at year 10.

IMPACT/APPLICATIONS

As ocean models have become multi-disciplinary research tools, a variety of applications from coastal to global scale and from physical to biogeochemical problems require numerical model to be flexible and highly optimized (Haidvogel and Beckmann 1999). There is a community-wide need to coordinate the development, testing, maintenance, and sharing of ocean models. The restrictions among the model classes should be reduced, if possible, to allow easy communication and coordination. Our proposed adaptive vertical coordinate system provides the capability for ocean modelers to share a common modeling platform and will benefit the scientific and operational ocean modeling community at large.

TRANSITIONS

The developed adaptive vertical coordinate scheme and tested results will be made available on-line (via the Internet) to the community for further applications. We will be responsible for questions and for providing help to implement the technique into other community models.

RELATED PROJECTS

The developed adaptive vertical coordinate capability can be readily applied to several national programs for modeling studies, including the ONR Eastern Boundary Current (CBE) program, the NOAA/NSF Global Ocean Ecosytem Dynamics (GLOBEC) project, the NSF Coastal Ocean Process (CoOP) program, and the NOAA Coastal Watch program. Specifically, the proposed work will contribute to NASA funded project, "Study the Coastal Ocean Response to the Time-Space Variability of Atmospheric Forcing Using QuickSCAT Winds and the Multi-Scale Ocean Models", for which Song is the PI. The improved capability in the ROMS will directly benefit the NASA effort to model the U. S. west coast circulation and variability.

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